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DISCOVERY OF NEW ULTRACOOL WHITE DWARFS IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

We report the discovery of five new white dwarfs in the Sloan Digital Sky Survey. Four are ultracool, exhibiting strong collision-induced absorption (CIA) from molecular hydrogen and are similar in color to the three previously known coolest white dwarfs, SDSS J1337+00, LHS 3250, and LHS 1402. The fifth star shows milder CIA flux suppression and has a color and spectral shape similar to WD 0346+246. All five new white dwarfs are faint ($g > 18.9$) and have significant proper motions. One of the new ultracool white dwarfs, SDSS J0947, appears to be in a binary system with a slightly warmer ($T_{\rm eff} \sim 5000$ K) white dwarf companion.

Subject headings: stars: individual (SDSS J0854+35, SDSS J0947+44, SDSS J1001+39, SDSS J1220+09, SDSS J1403+45) — white dwarfs

1. INTRODUCTION

White dwarf (WD) stars with $T_{\rm eff} < 4000$ K are of great interest for several reasons. The end-stage remnants of main-sequence stars with masses less than about 8 $M_\odot$, they represent some of the oldest objects in the Galaxy. As such, they give direct information about star formation during the Galaxy's earliest epochs. Since WDs continue to cool and fade with time, the very coolest can place lower limits on the ages of various galactic components. In addition, recent microlensing searches have suggested that there may be a significant population of WDs in the Galactic halo (Alcock et al. 2000), offering a window into the early stages of the Galaxy and its formation.

Progress in modeling cool WDs has helped to refocus the search for these objects (Hansen 1998; Saumon & Jacobson 1999; Bergeron & Leggett 2002). In pure hydrogen atmosphere WDs with temperatures below about 5000 K, collision-induced absorption (CIA) by molecular hydrogen results in an infrared flux suppression; below about 3000 K CIA becomes strong enough to impact the optical spectrum as well, shifting the colors of the star blueward. In stars with mixed H/He atmospheres, the CIA opacity increases with increasing He abundance until it reaches a maximum strength at $N[{\rm H}]/N[{\rm He}] \sim 10^{-5}$. Thus, CIA becomes significant in mixed atmosphere models at higher $T_{\rm eff}$, and the optical colors become bluer for temperatures below about 4000 K. In this Letter we use ultracool to denote very cool WDs with strong CIA flux suppression such that optical colors have been affected, indicating $T_{\rm eff} <$ 4000 K regardless of atmospheric composition. To date, three ultracool WDs have been observed—LHS 3250 (Harris et al. 1999, 2001; Oppenheimer et al. 2001b), SDSS J133739.40+0001428 (hereafter SDSS J1337; Harris et al. 2001), and LHS 1402 (Oppenheimer et al. 2001a; Salim et al. 2004)—confirming the general predictions of the models. A second group of very cool WDs exhibiting milder CIA flux suppression has also been found: WD 0346+246 (Hambly et al. 1997; Hodgkin et al. 2000; Oppenheimer et al. 2001b), LHS 1126 (Bergeron et al. 1994, 1997), and GD 392B (Farihi 2004) exhibit a significant flux deficiency in the near-infrared. A handful of cool WDs may belong to this second group but lack infrared data, including a wide binary pair of WDs, SSSPM J2213−7514 and J2213−7515 (Scholz et al. 2002), F351−50 (Ibata et al. 2000), and CE 51 (Ruiz & Bergeron 2001).

The unusual colors of ultracool WDs led to predictions (Harris et al. 1999; Hansen 2001) that they should be detectable in the Sloan Digital Sky Survey (SDSS; York et al. 2000, Abazajian et al. 2003, 2004, Gunn et al. 1998, Stoughton et al. 2002). The colors of these coolest WDs lie in a region of color-color space distinct from that of most stars and sparsely populated by high-redshift ($z > 3$) QSOs. Two ultracool WDs were picked up in the commissioning data of the SDSS (the new discovery SDSS J1337+00 and the previously known LHS 3250; see references above). In this Letter we report the discovery of new ultracool WDs in the SDSS. We have found four stars exhibiting strong CIA, similar to LHS 3250 and SDSS J1337+00, more than doubling the number of known WDs with strong flux suppression. We also report the discovery of a fifth star with milder CIA suppression and colors closer to those of the second group exemplified by WD 0346+246.

2. OBSERVATIONS

WDs exhibiting strong CIA have a high probability of being selected for spectroscopic observations by SDSS as possible high-redshift quasars as well as cool WDs (Harris et al. 2001). We have performed a thorough search of all SDSS (Pier et al. 2003; Smith et al. 2002; Hogg et al. 2001) spectral data available as of 2004 April (approximately 50% of the total number of spectra that will ultimately be targeted by SDSS). All spectra were obtained with the SDSS 2.5 m telescope multifiber spectrographs, which cover 3800–9200 Å at a spectral resolution of 1800 (York et al. 2000). The featureless spectra of WDs that are cool enough to exhibit CIA are classified as unknown by the SDSS spectroscopic pipeline, and we visually examined all SDSS unknown spectra.

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TABLE 1
OBSERVATIONAL DATA

Parameter	SDSS J0947	SDSS J1220	SDSS J1001	SDSS J0854	SDSS J1403
R.A.	09 47 23.0	12 20 48.7	10 01 03.4	08 54 43.3	14 03 24.7
Decl.	44 59 49	09 14 12	39 03 40	35 03 53	45 33 33
μ (mas yr^{-1})	86	504	353	223	284
μ_α (mas yr^{-1})	74 ± 4	-341 ± 15	-301 ± 3	-133 ± 5	-271 ± 3
μ_δ (mas yr^{-1})	45 ± 3	-372 ± 15	-185 ± 3	-179 ± 5	-84 ± 3
u	20.71	22.40	21.39	23.63	20.14
g	19.45	20.35	20.04	20.49	18.93
r	18.85	19.34	19.58	19.38	19.02
i	18.92	19.42	19.99	19.07	19.51
z	19.40	19.89	20.51	18.92	19.82
d (pc)	21–52	28–71	28–71	30–74	19–49
$v_{\rm tan}$ (km s^{-1})	8–21	68–170	47–119	31–78	26–66
Julian epoch	2002.023	2002.192	2002.998	2002.850	2003.176
MJD/plate/fiber[a]	52672/1202/33	52672/1230/58	53033/1356/280	52964/1211/395	53115/1467/401

NOTES.—Coordinates are given for equinox J2000.0. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] SDSS spectra information.

The five new WDs reported here are SDSS J094722.98+445948.5, SDSS J122048.65+091412.1, SDSS J100103.42+390340.4, SDSS J140324.66+453332.6, and SDSS J085443.33+350352.7 (hereafter SDSS J0947, SDSS J1220, SDSS J1001, SDSS J1403, and SDSS J0854, respectively). Their positions, proper motions, and colors are given in Table 1.[9] Preliminary proper motions were calculated using the SDSS and USNO-B catalog positions, but in at least two cases these proper motions were clearly unreliable. We hence returned to the POSS I, II, and SDSS images and obtained proper-motion measurements by direct reduction. The five new objects all have highly significant proper motions, and SDSS J0947 has a proper-motion companion (see § 4).

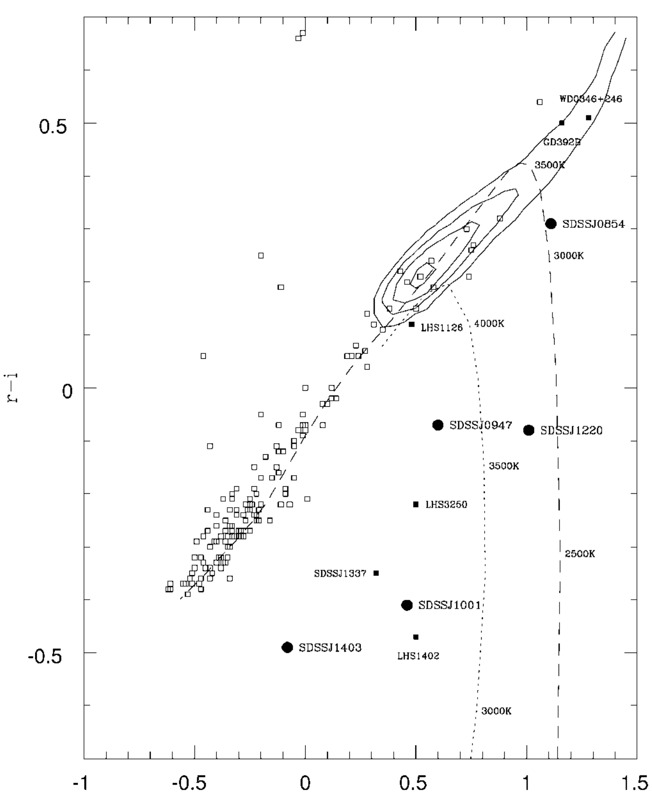

FIG. 1.—Color-color diagram showing five new WDs (*solid circles*) and previously known ultracool WDs (*solid squares*) for which we were able to estimate SDSS colors (see text for more details). A sample of normal WDs (*open squares*) and contours that show the colors of nondegenerate stars in SDSS are included for comparison. Model predictions for pure H (*dashed line*) and N[H]/N[He] $= 10^{-5}$ (*dotted line*) atmospheres (courtesy P. Bergeron) are also shown.

The colors of the new WDs are shown in Figure 1. For comparison, we have also plotted the other known very cool WDs,[10] as well as the locus of points for a sample of normal WDs in the SDSS (Kleinman et al. 2004). The unusual colors of the four new stars with strong CIA flux suppression—SDSS J0947, SDSS J1220, SDSS J1001, and SDSS J1403—are evident in this plot. SDSS J0854 exhibits milder CIA suppression and lies much closer to the locus of warmer WDs. However, the spectra for all five new stars are distinctive, as can be seen in Figure 2. All are featureless and show a noticeable flux suppression at wavelengths longer than about 6000 Å. The spectra of SDSS J0947 and SDSS J1001 are very similar to each other and also to LHS 3250. SDSS J1403 exhibits the most severe flux suppression, while the spectrum of SDSS J1220 is somewhat more sharply peaked than the others, with a steeper slope blueward of the peak.

3. TEMPERATURE AND ATMOSPHERIC COMPOSITION

Studies of previously known very cool WDs have found that these stars are likely to have He-rich atmospheres, although even He-rich models fail to accurately reproduce the observed spectra in detail (Bergeron & Leggett 2002). With the addition of five new stars the classification of very cool WDs into two rough groupings, based on their colors and amount of CIA suppression, persists. (However, we note that this grouping may not necessarily indicate any underlying physical distinction between the stars other than temperature.)

In the first group are SDSS J1337, LHS 3250, SDSS J0947,

[9] Finding charts for each new star can be found at http://astro.uchicago.edu/~gates/findingcharts.

[10] SDSS colors for very cool WDs without SDSS data were estimated using the photometric transformations of Fukugita et al. (1996), expected to be accurate to about 0.1 mag. The one exception to this was the $r - i$ color of LHS 1402, which we extracted from its shape-calibrated spectrum (B. Oppenheimer 2004, private communication). We were unable to obtain sufficient color data for F351-50 to estimate SDSS colors.

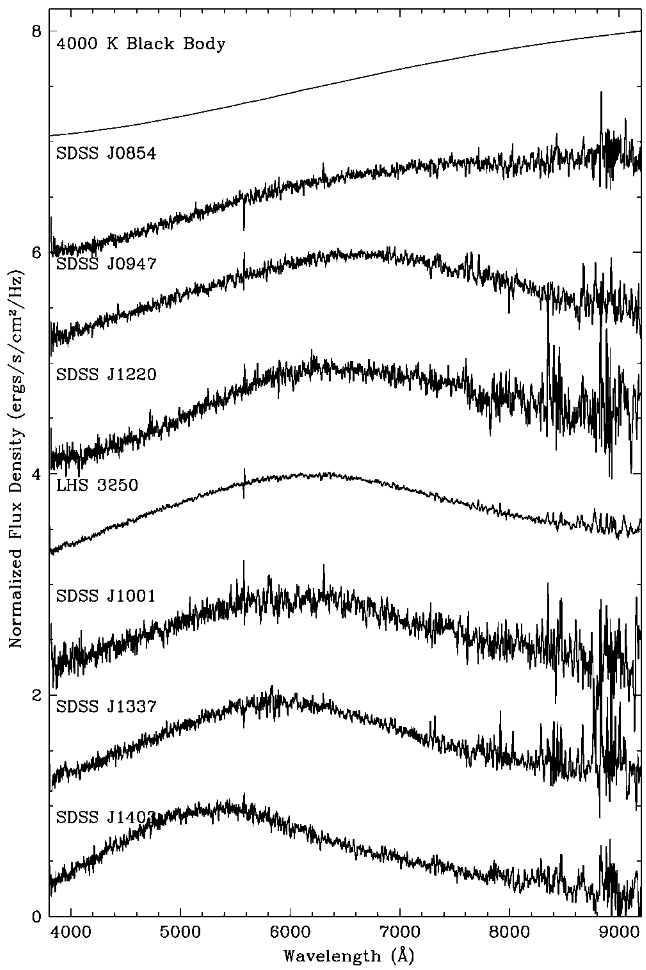

FIG. 2.—Spectra for seven ultracool WD stars observed in the SDSS data, including five new stars. Spectra are offset vertically from each other and a 4000 K blackbody SED is also shown for comparison. (Spectra have been smoothed by 5 pixels.)

SDSS J1220, SDSS J1001, LHS 1402, and SDSS J1403. All seven lie in the same region of color-color space, well below the locus of normal WDs, and exhibit strong CIA suppression indicating temperatures below about 4000 K. If the relative position in color-color space indicates a progression downward in temperature as the cool WDs fall farther from the cool end of the normal WD locus, SDSS J1403 may be the coolest WD yet discovered. Bergeron & Leggett (2002) were able to rule out pure hydrogen atmospheres for LHS 3250 and SDSS J1337 and, despite the imprecision of the spectral energy distribution (SED) fit with a high He/H composition, concluded that these objects are likely to be overluminous, He-rich, low-mass binaries (Harris et al. 1999; Bergeron & Leggett 2002). While the spectra of SDSS J1001, SDSS J0947, and SDSS J1403 are similar to LHS 3250, trigonometric parallaxes and detailed model fitting are necessary before strong conclusions regarding their nature can be reached. The fourth new star, SDSS J1220, shows significant CIA suppression but lies a bit farther apart in color space from the others in the first group. Its spectral shape exhibits a relatively sharp peak, with a steep falloff in flux both before and beyond about 6000 Å, which may indicate a different atmospheric composition from the others. However, until more detailed model comparisons can be made, no strong conclusions are possible. We expect that this object also lies in the broad temperature range of 2000–4000 K, possibly toward the cooler end, especially if the atmosphere has a low helium abundance.

The second group includes WD 0346+24, F351−50, GD 392B and LHS 1126, and possibly SSSPM J2231−7514, SSSPM J2231−7515, and the new star SDSS J0854. All of these stars lie close to the normal WD locus in color space and cannot be distinguished from the locus of ordinary stars based on optical color alone. They exhibit milder CIA flux suppression and may have temperatures closer to or above 4000 K. LHS 1126, for example, is well fitted by a mixed H/He model with $T_{\rm eff} = 5400$ K (Bergeron et al. 1994).

Like all three of the previously known ultracool WDs, none of our new WDs exhibits the H_2 feature at roughly 8000 Å predicted by the models, despite the use of the latest opacities calculated for H_2 (Borysow et al. 2001; Jørgensen et al. 2000). We note that this feature is minimized in helium-rich models. Also shown in Figure 1 are (P. Bergeron 2003, unpublished) model predictions for pure H and mixed H/He atmosphere WDs (constant $\log g = 8.0$). Note that most of the stars lie blueward in g-r of even the mixed $N[{\rm H}]/N[{\rm He}] = 10^{-5}$ curve, at which abundance the opacity is believed to be strongest. As is clear from the figure, further improvements in either the opacities or the models (e.g., Kowalski & Saumon 2004; Iglesias et al. 2002) will be needed to extract more accurate estimates of the temperatures and compositions of these stars.

4. DISK OR HALO?

Assigning membership of these new stars to a particular component of the galaxy is problematic because extracting reliable absolute magnitudes from comparison to theoretical models is not yet possible. For example, the parallax of LHS 3250 implies an absolute magnitude $M_V = 15.72 \pm 0.04$ (Harris et al. 1999), much brighter than that predicted by models of normal-mass, hydrogen atmosphere WDs that have cooled to temperatures where CIA becomes significant in the optical spectra. If we consider LHS 3250 as a paradigm for the WDs in the first group and assume a similar absolute magnitude, we find a distance of $d \sim 47$ pc and a corresponding $v_{\rm tan} \sim 20$ km s^{-1} for SDSS J0947. For SDSS J1001, we find $d \sim 64$ pc and $v_{\rm tan} \sim 107$ km s^{-1}, while for SDSS J1403 we obtain $d \sim 44$ pc and $v_{\rm tan} \sim 60$ km s^{-1}. Likewise, SDSS J1220, which has the highest proper motion, has $d \sim 64$ pc and $v_{\rm tan} \sim 154$ km s^{-1}. Furthermore, SDSS J0947 has a companion 20″ away with common proper motion: SDSS J094724.45+450001.8 has colors consistent with a WD of $T_{\rm eff} \sim 5000$ K at a distance of about 60 pc with a tangential velocity of 25 km s^{-1}. If this distance is correct, then like LHS 3250 the absolute magnitude of SDSS J0947 is brighter than that predicted by the models for a cool halo WD of normal mass, and it adds to the evidence that it is a disk star with a large radius and small mass. We can use a similar approach for WDs in the second group. If we assume the absolute magnitude of SDSS J0854 is similar to that of WD 0346+246 ($M_V = 16.8 \pm 0.3$ based on its parallax distance; Hambly et al. 1999), we find $d \sim 41$ pc and $v_{\rm tan} \sim 43$ km s^{-1}.

A more conservative approach for all of the new WDs is to consider a value for the absolute magnitude of $M_V = 16.5 \pm 1.0$, following Salim et al. (2004). This range encompasses a wide suite of model predictions for an $m = 0.6\ M_\odot$, pure H or mixed H/He white dwarf that exhibits CIA flux suppression. The results are given in Table 1. Based on these estimates of $v_{\rm tan}$, it is clear that SDSS J0947 and SDSS J0854 are members of the Galactic disk, and SDSS J1403 probably is as well. SDSS J1001 may be either disk or halo; however, if it has the bright $M_V < 16$ required for the larger values of $v_{\rm tan}$, it must also have a large radius and low mass similar to that implied for LHS 3250 (Harris et al. 2001). SDSS J1220 is likely to be a halo WD, which makes its unusual colors and steep flux suppression even more interesting. It is the only ultracool WD known that can be a halo star with normal mass that has cooled to a temperature substantially lower than WD 0346+246. Ultimately, of course, trigonometric parallax measurements will be necessary to fully understand these stars.

Based on the six stars with strong CIA detected in ~4330 deg^2 of sky observed for SDSS spectra through 2004 April, we find a density of 0.0014 deg^{-2} ultracool WDs with $i < 20.2$ (the magnitude limit for selection of QSO candidates), or approximately $R < 19.8$. This is somewhat higher than that found by Oppenheimer et al. (2001a), who found one star (LHS 1402) in 4200 deg^2 with $R < 19.8$ and $\mu > 330$ mas yr^{-1} (three of our six stars are within these limits) and is consistent with the Luyten half-second (LHS) catalog that has two stars with $R < 18$ and $\mu >$ 500 mas yr^{-1} (although the LHS limiting magnitude varies over the sky). To estimate their space density, we note that nearly all ultracool WDs will be selected for spectra by one or both of the QSO selection algorithms (Richards et al. 2002). The magnitude limits are $i < 19.1$ for low-z QSO candidates and $i < 20.2$ for redder high-z candidates. In fact, all six strong-CIA stars were flagged by the QSO selection procedure, and four were assigned fibers as QSO candidates.[11] Assuming these four stars are similar to LHS 3250 ($M_r = 15.47$), and summing the inverse of their potential discovery volumes, we find a space density of 3.0×10^{-5} pc^{-3} (with large uncertainties due to uncertain distance and luminosity estimates), similar to the density of the disk WD luminosity function at the faintest measured luminosity bin (Leggett et al. 1998). Our estimate may reflect a mix of various galactic components.

The status of SDSS J0947 as a member of a binary system is far from unique. CE 51 has a main-sequence companion, GD 392B has a probable WD companion, and SSSPM J2231−7514 and SSSPM J2213−7515 are a wide binary pair. Thus, if the presence of CIA is confirmed in these latter three stars, ~30% of the known WDs exhibiting CIA would be in binary systems.

In summary, we have discovered five new WDs in the SDSS. Four have colors and spectra indicating strong CIA, and one appears to have the strongest CIA of any star discovered to date. Only one star has a proper motion sufficiently large that it is likely to be a halo star with low luminosity and normal mass. Three of the others have smaller proper motions, indicating that they are probably disk stars with younger ages, higher luminosities, and smaller masses, and one of these three has a warmer WD companion with a photometric distance supporting the small-mass interpretation. The fifth star has a proper motion that could be either disk or halo, but for higher tangential velocities it must also have a high luminosity and low mass. None of the spectra exhibit bands of H_2, thus favoring He-rich atmospheres for these objects. Finally, we find a rough estimate of the density of ultracool WDs of about 3.0×10^{-5} pc^{-3}.

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[11] Of the other two, SDSS J1001 was too faint for low-z selection so was flagged as QSO_MAG_OUTLIER, and SDSS J1403 had colors in the A-star reject box so was flagged as QSO_REJECT. Both were observed anyway by the backup SERENDIPITY_DISTANT. Because SERENDIPITY and other non-QSO selection categories are not complete, we omit these two stars from the calculation of space density. The faint magnitude limits for these categories imply large discovery volumes, and thus we expect the density contributions will be small in any case.

[12] The SDSS Web site is http://www.sdss.org.

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